THE DETECTION OF BRIGHT ASYMPTOTIC GIANT BRANCH STARS IN THE NEARBY ELLIPTICAL GALAXY MAFFEI 1

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ABSTRACT

We have used the adaptive optics system on the Canada-France-Hawaii Telescope to study a field 6 arcmin from the center of the heavily obscured elliptical galaxy Maffei 1. Our near diffraction-limited H and K' images reveal an excess population of objects with respect to a background field, and we conclude that the asymptotic giant branch tip (AGB-tip) in Maffei 1 occurs at $K = 20 \pm 0.25$. Assuming that stars at the AGB-tip in Maffei 1 have the same intrinsic luminosity as those in the bulge of M31, then the actual distance modulus of Maffei 1 is 28.2 ± 0.3 if $A_V = 5.1$, which corresponds to a distance of $4.4^{+0.6}_{-0.5}$ Mpc. This is in excellent agreement with the distance estimated from surface brightness flucuations in the infrared, and confirms that Maffei 1 is too distant to significantly affect the dynamics of the Local Group.

Subject headings: galaxies: individual (Maffei 1) – galaxies: distances and redshifts

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1. INTRODUCTION

The elliptical galaxy Maffei 1 (Maffei 1968) is one of the dominant members of a group that includes the spiral galaxy IC 342 (van den Bergh 1971). This group of galaxies contains some of the largest extragalactic objects in the northern sky (Buta & McCall 1999), indicating that Maffei 1 and its companions are relatively close. In fact, with the possible exception of NGC 5128, which has a distance of 3.9 Mpc (Harris, Harris, & Poole 1999), Maffei 1 may be the nearest giant elliptical galaxy and, despite being located at low Galactic latitudes, is thus an important benchmark for studies of these systems. Moreover, if Maffei 1 is as close as 2 Mpc (Buta & McCall 1983), then it could significantly affect the dynamics of the Local Group, which could then no longer be considered as a simple two-body system (Valtonen et al. 1993; Zheng, Valtonen, & Byrd 1991). This has potential cosmological implications, as Local Group timing arguments provide a direct geometrical constraint on the mass of the Galaxy and M31 (e.g. Kahn & Woltjer 1959) and, by extension, the dark matter content of galaxies.

Buta & McCall (1999) list radial velocities for 13 members of the IC 342/Maffei group, and the mean is $< v_0 >= +30 \pm 25$ km sec^{-1} with a dispersion 89 ± 25 km sec^{-1}. Using equation 6 of Courteau & van den Bergh (1999), the mean velocity of this group relative to the Local Group center is then +279 km sec^{-1}, which significantly exceeds the velocity dispersion of the Local Group (61 ± 8 km sec^{-1}; Courteau & van den Bergh 1999). Thus, the radial velocity of the IC 342/Maffei group is consistent with these objects being well outside the Local Group. However, there is a sizeable spread in the distances that have been estimated for Maffei 1 and its companions. Using the Faber-Jackson relation, Buta & McCall (1983) concluded that the distance to Maffei 1 is $2.1^{+1.3}_{-0.8}$ Mpc. More recently, Luppino & Tonry (1993) obtained a distance of 4.2 $\pm$0.5 Mpc using surface brightness flucuations in K, and 4.2 ± 1.1 Mpc based on the $\mathrm{D}_n - \sigma$ relation. The distances to other members of the IC 342/Maffei group have been estimated by McCall (1989), Krismer, Tully, & Gioia (1995), Karachentsev et al. (1997) and Ivanov et al. (1999), and the results fall between 1.7 and 5.3 Mpc. While this large range in distances may call into question the reality of an IC 342/Maffei group, many of the distance estimates have large uncertainties, due in part to the significant amount of reddening towards these objects. The radial velocity dispersion of the IC 342/Maffei group deduced from the Buta & McCall (1999) data, quoted in the opening sentence of this paragraph, is not significantly different from that of the Local Group derived by Courteau & van den Bergh (1999), and this would likely not be the case if the galaxies were spread out over 3.5 Mpc.

The large range of distances measured, and inferred, for Maffei 1 and its companions underscores the need to obtain additional distance estimates. Direct constraints on the

distance to Maffei 1 can be obtained from the photometric properties of resolved stars in this galaxy. A complicating factor is that Maffei 1 is viewed at low Galactic latitudes, and efforts to probe the stellar content of this galaxy must deal with contamination from stars in the Galactic disk and extinction by interstellar dust. The extinction towards Maffei 1 is considerable, with $A_V = 5.1 \pm 0.2$ mag (Buta & McCall 1983), and so efforts to study the resolved stellar content of this galaxy are restricted to the infrared. If the distance to Maffei 1 is not greater than 10 Mpc, and this galaxy has an AGB content similar to that in the bulge of M31, which peaks at $K = 15.6 \pm 0.1$ (Davidge 2001a), then the brightest stars should be detectable in the near-infrared using a 4 meter telescope equipped with an adaptive optics (AO) system. In the current paper, we discuss a preliminary reconnaisance of the stellar content of a field 6 arcmin from the center of Maffei 1 using deep H and K' images with angular resolutions approaching the diffraction limit of the 3.6 metre Canada-France-Hawaii Telescope (CFHT).

2. OBSERVATIONS AND REDUCTIONS

The data were recorded with the CFHT AO Bonette (Rigaut et al. 1998) and KIR imager during the nights of UT 2000 September 10 and 11. KIR contains a 1024×1024 Hg:Cd:Te array with 0.034 arcsec pixels, and thus images a 34×34 arcsec field.

Two fields were observed through H and K' (Wainscoat & Cowie 1992) filters. One field, centered on the AO reference star GSC 03699-00675 ($\alpha = 02^h36^m05^s$, $\delta = +59^o34'29''$ J2000) samples Maffei 1 at a projected distance of 6 arcmin from the galaxy center. This field was selected based on (1) the surface brightness of Maffei 1, which the measurements given by Buta & McCall (1999) suggested was sufficiently low at this galactocentric radius to permit individual stars on the upper magnitude of the RGB to be resolved with the AO system during median seeing conditions, and (2) the availablity of an AO reference star. This field will be referred to as the 'galaxy' field for the remainder of the paper. The second field, which will be referred to as the 'background' field, is located 25 arcmin from Maffei 1, and is centered on the AO reference star GSC 03699 - 01721 ($\alpha = 02^h36^m47^s$, $\delta = +59^o09'06''$ J2000).

The data were obtained in sets of five 60 sec exposures, which were recorded at each corner of a 0.5×0.5 arcsec square dither pattern. The dither sequence was repeated to increase signal from faint sources. The total exposure time for the galaxy field was 160 minutes per filter, while for the background field the total exposure time was 60 minutes per filter.

The data were reduced using the procedures discussed by Davidge & Courteau (1999), and the final images have FWHM = 0.14 arcsec (H) and 0.15 arcsec (K').

3. RESULTS

The brightnesses of individual stars were measured with the point-spread-function (PSF) fitting routine ALLSTAR (Stetson & Harris 1988), and the instrumental measurements were transformed into the standard system using coefficients derived from observations of faint UKIRT standard stars (Casali & Hawarden 1992). A single PSF was constructed for each image using tasks in DAOPHOT (Stetson 1987); while anisoplanicity causes the PSF to vary with distance from the guide star, past experience with the CFHT AO system indicates that these variations do not dominate the uncertainties in the photometry over the KIR field (Davidge & Courteau 1999; Davidge 2001b). Speckle noise hinders the detection of faint sources near the relatively bright AO guide stars (Racine et al. 1999), and so the area within 3 arcsec of the guide star in each field was excluded from the photometric analysis.

Artificial star experiments were used to estimate completeness and assess systematic effects in the photometry. Artificial stars with $H - K$ colors similar to those of detected objects, and in numbers small enough to prevent artificially increasing the degree of crowding, were added to the images of each field. Photometry of the artificial stars indicate that (1) systematic errors in the measured brightnesses exceed 0.1 mag when $K \geq 21.5$, and (2) the completeness fractions in the galaxy and background fields are similar when $K \leq 21.5$; hence, $K = 21.5$ is adopted as the faint limit for these data. While the galaxy field might be expected to go slightly deeper than the background field because of the difference in integration times, this is not the case because of the greater degree of crowding among faint objects in the galaxy field.

Massive elliptical galaxies have sizeable, centrally-concentrated globular cluster populations. Buta & McCall (private communication) have detected resolved objects in WFPC2 images centered on the core of Maffei 1, and they suggest that these are globular clusters. We have not detected similar objects in our galaxy field; this null detection is perhaps not surprising given (1) the modest field size, and (2) that we observed the outer regions of the galaxy, where the density of clusters is low.

The $(K, H - K)$ color-magnitude diagrams (CMDs) of the galaxy and background fields are compared in Figure 1. Main sequence stars in the Galactic disk form a locus with $H - K$ between 0 and 0.4 that dominates the bright portions of both CMDs. The main

sequence locus has similar colors in both fields, indicating that the reddenings along the two sight lines are not vastly different.

The $(K, H - K)$ CMD of the galaxy field contains a population of red objects with $K > 20.5$ that is not seen in the background field. The statistical significance of these faint stars can be investigated by comparing the K luminosity functions (LFs) of the galaxy and background fields, and this is done in Figure 2. The LFs in this figure were constructed from sources detected in both filters. The LFs of both fields show qualitatively similar behaviour at the bright end, rising slowly from $K = 15$ to $K = 20$; however, at $K = 20.5$ the LF of the galaxy field departs from this trend. The difference between the LFs of the galaxy and background fields shows an excess at $K = 20.5$ that is significant at the 2.3σ level; at fainter levels the statistical significance of the excess population becomes even greater.

It is evident from Figure 1 that the galaxy field contains more Galactic disk stars than the background field, and the ratio of objects with K between 15 and 20 in these fields is $33/17 = 1.9 \pm 0.6$; this difference could be due to stochastic variations in star counts, clustering, and/or differential absorption. To investigate the extent to which the difference in foreground star counts affects the statistical significance of any faint population in the galaxy field, the background field LF was scaled up by a factor of 1.9, and the difference between the galaxy field and scaled background field LFs is shown in the bottom panel of Figure 2. Even after scaling the background field LF, the galaxy field LF still contains an excess number of objects when $K > 20.5$, indicating that the faint population detected in the galaxy field is not an artifact of field-to-field variations in foreground star counts. We thus conclude that the faint stars seen in the galaxy field belong to Maffei 1.

4. DISCUSSION

The distance to Maffei 1 can be estimated to an internal accuracy of ± 0.25 mag based on the star counts in the galaxy field. To demonstrate this, assume $A_V = 5.1$ (Buta & McCall 1983) and a preliminary distance of 4.2 Mpc (Luppino & Tonry 1993). Since the surface brightness of Maffei 1 in the galaxy field is $\mu_V = 27$ mag arcsec^{-2} based on the Buta & McCall (1999) light profile, the total integrated brightness in this field is $M_V = -13.8$. Davidge (2001a) discusses observations of a field in the bulge of M31 with almost the same integrated intrinsic brightness as the Maffei 1 galaxy field, and found 4 stars within 0.5 mag of the AGB-tip. The number density of stars climbs rapidly with decreasing brightness in the M31 bulge field, and there are 58 stars in the next 0.5 mag interval. If the stellar content of the Maffei 1 galaxy field is like that in the M31 bulge then (1) the number of

stars within 0.5 mag of the AGB-tip will be modest, to the point where they may not be detectable above the statistical noise in the background counts, and (2) there will be a rapid increase in the stellar density in the next 0.5 mag interval. Thus, while it might be straight-forward to detect an AGB component given the steeply rising LF within 1 mag in K of the AGB-tip, small number statistics in the top 0.5 mag mean that the AGB-tip can likely not be identified to better than ±0.25 mag in fields at moderately large distances from the galaxy center.

After correcting for incompleteness and subtracting background star counts, we find that there are 35 ± 15 stars with K between 20.25 and 20.75 in the galaxy field, suggesting that this brightness interval samples the AGB roughly 0.5 mag below the AGB-tip. We thus consider $K = 20.25$ (i.e. the bright edge of the $K = 20.5$ bin) to be the faint limit of the AGB-tip in Maffei 1, while the AGB-tip will likely not be brighter than $K = 20.25 - 0.5 = 19.75$; hence, we adopt $K = 20.0 \pm 0.25$ as the brightness of the AGB-tip.

Davidge (2001a) finds that the brightest stars in M32, the bulge of M31, and the Galactic bulge have similar infrared brightnesses, with $\mathrm{M}_K = -8.9 \pm 0.1$, suggesting that the AGB-tip can be used as a standard candle to estimate the distance to Maffei 1. We estimate the distance to Maffei 1 in a differential manner with respect to M31. The brightest stars in the bulge of M31 have $K = 15.6 \pm 0.1$ and so the difference in distance modulus between this galaxy and Maffei 1 is $\Delta\mu_0 = 20.0 \pm 0.25 - 15.6 \pm 0.1 = 4.4 \pm 0.3$. If $\mu_0 = 24.4 \pm 0.1$ for M31 (van den Bergh 2000), $\mathrm{A}_V = 5.1 \pm 0.1$ for Maffei 1 (Buta & McCall 1983), and $\frac{A_K}{A_V} = 0.11$ (Rieke & Lebofsky 1985), then the unreddened distance modulus of Maffei 1 is 28.2 ± 0.3, which is in good agreement with the Luppino & Tonry (1993) surface brightness flucuation result ($\mu_0 = 28.1 \pm 0.3$). It is worth noting that the stars that dominate surface brightness flucuations in the infrared have $\mathrm{M}_K = -5.6$ (Luppino & Tonry 1993); not only are these stars significantly fainter than the AGB stars detected in the current study, but they are also likely evolving on the first ascent giant branch. Thus, the distances estimated here and by Luppino & Tonry (1993) rely on very different stars, and are in this sense independent.

The RGB-tip, which occurs ~ 2 mag in K below the AGB-tip in nearby galaxies (e.g. Davidge 2000), provides another means of estimating the distance to Maffei 1. The results in the current study suggest that the RGB-tip in Maffei 1 should appear near $K = 22.0$, which is within the detection threshold of 8 metre class telescopes equipped with AO systems. In any event, if Maffei 1 were as close as 2 Mpc then the RGB-tip would occur at $K = 20$, and this is clearly inconsistent with the data presented here; Maffei 1 is therefore too distant to significantly affect the dynamics of the Local Group.

We close by noting that our distance to Maffei 1 is consistent with a smooth local

Hubble flow just outside the Local Group (Sandage 1986, Ekholm et al. 2001). Assuming a smooth Hubble flow with $H_0 = 72 \pm 8$ km sec^{-1} Mpc^{-1} (Freedman et al. 2000) and a recession velocity of 279 ± 25 km sec^{-1} (§1) for the IC 342/Maffei group yields a distance of 3.9 ± 0.6 Mpc, which is in excellent agreement with the distance of $4.4^{+0.6}_{-0.5}$ Mpc derived for Maffei 1 from AGB stars.

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REFERENCES

Buta, R. J., & McCall, M. L. 1983, MNRAS, 205, 131

Buta, R. J., & McCall, M. L. 1999, ApJS, 124, 33

Casali, M., & Hawarden, T. 1992, JCMT-UKIRT Newsletter, 4, 33

Courteau, S., & van den Bergh, S. 1999, AJ, 118, 337

Davidge, T. J. 2000, PASP, 112, 1177

Davidge, T. J. 2001a, AJ, submitted

Davidge, T. J. 2001b, AJ, in press

Davidge, T. J., & Courteau, S. 1999, AJ, 117, 1297

Davidge, T. J., Rigaut, F., Chun, M., Brandner, W., Potter, D., Northcott, M., Graves, J. E. 2000, ApJ, 545, L89

Ekholm, T., Baryshev, Y., Teerikorpi, O. M., Hanski, M. O., & Paturel, G. 2001, A&A, 368, L17

Freedman, W. L. et al. 2000, astro-ph 0012376

Harris, G. L. H., Harris, W. E., & Poole, G. B. 1999, AJ, 117, 855

Ivanov, V. D., Alonso-Herrero, A., Rieke, M. J., & McCarthy, D. 1999, AJ, 118, 826

Kahn, F. D. & Woltjer, J. 1959, ApJ, 130, 705

Karachentsev, I., Drozdovsky, I., Kajsin, S., Takalo, L. O., Heinamaki, P., Valtonen, M. 1997, A&AS, 124, 559

Krismer, M., Tully, R. B., & Gioia, I. M. 1995, AJ, 110, 1584

Luppino, G. A., & Tonry, J. L. 1993, ApJ, 410, 83

Maffei, P. 1968, PASP, 80, 618

McCall, M. L. 1989, AJ, 97, 1341

Racine, R., Walker, G. A. H., Nadeau, D., Doyon, R., & Marois, C. 1999, PASP, 111, 587

Rieke, G. H., & Lebofsky, M. J. 1985, ApJ, 288, 618

Rigaut, F. et al. 1998, PASP, 110, 152

Sandage, A. 1986, ApJ, 307, 1

Stetson, P. B. 1987, PASP, 99, 191

Stetson, P. B., & Harris, W. E. 1988, AJ, 96, 909

Valtonen, M. J., Byrd, G. G., McCall, M. L., & Innanen, K. A. 1993, AJ, 105, 886

van den Bergh, S. 1971, Nature, 231, 35

van den Bergh, S. 2000, The Galaxies of the Local Group, Cambridge Press, 11

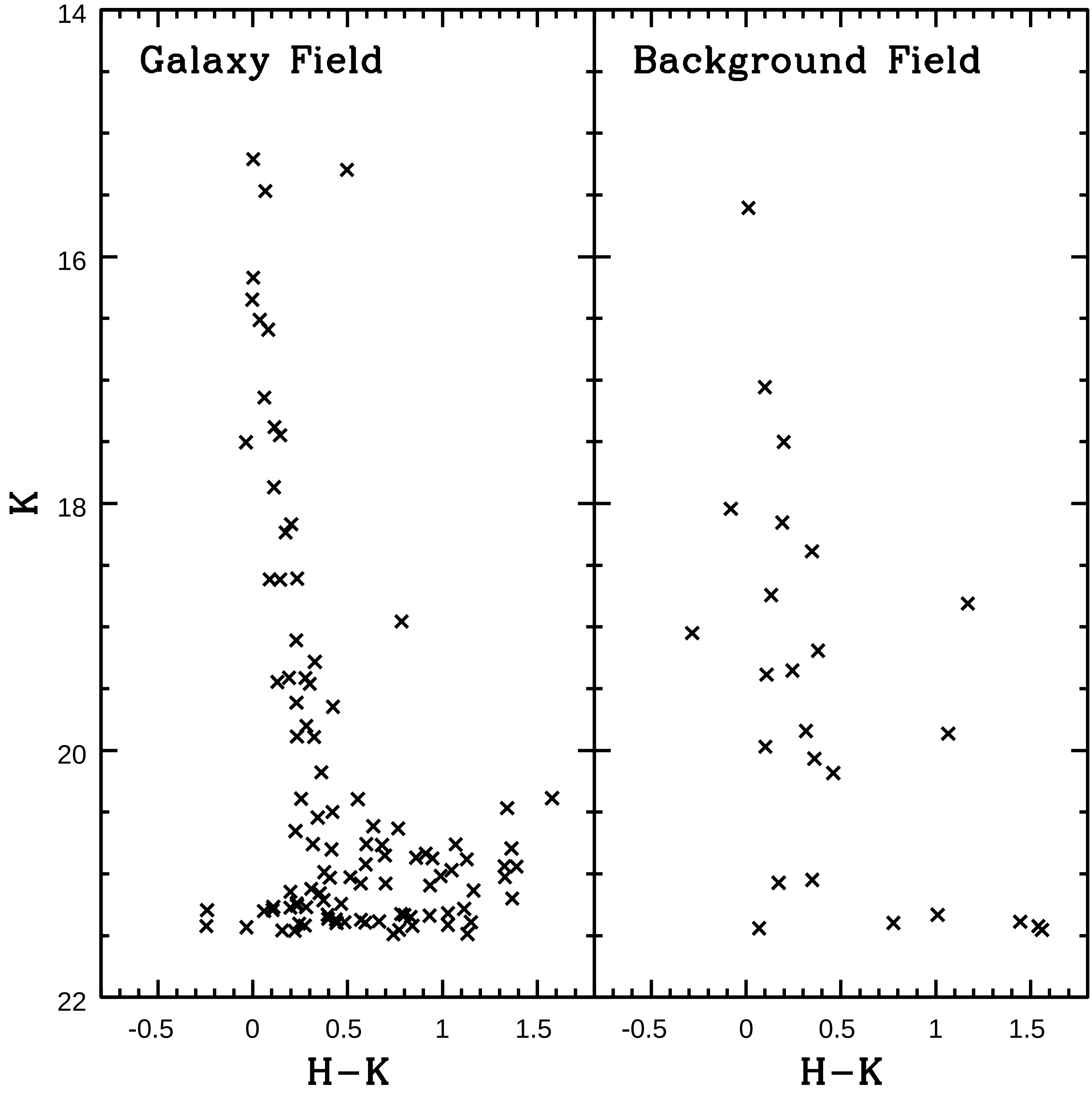
Wainscoat, R. J., & Cowie, L. L. 1992, AJ, 103, 332

Zheng, J.-Q., Valtonen, M. J., & Byrd, G. G. 1991, A&A, 247, 20

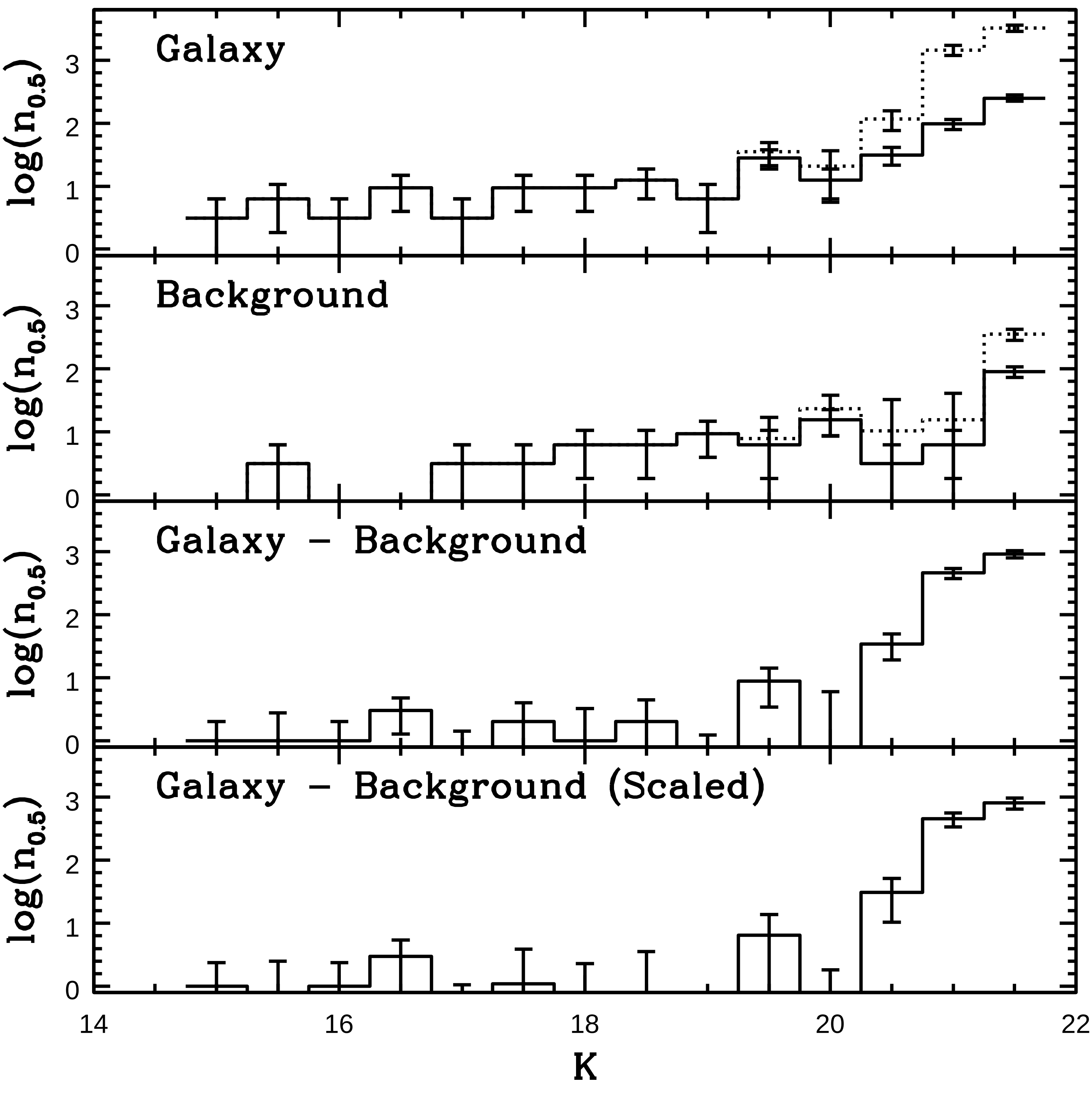
FIGURE CAPTIONS

Fig. 1.— The $(K, H-K)$ CMDs of the galaxy and background fields. The locus of points with $K < 20$ in each CMD is produced by main sequence stars in the Galactic disk. Note that the colors of the main sequence component in each field are similar, indicating that the mean reddenings along the two sight lines are not greatly different. The population of red objects with $K > 20.5$ in the galaxy field are identified as stars in Maffei 1.

Fig. 2.— The K LFs of the galaxy and background fields (top two panels), and their differences (lower two panels). $n_{0.5}$ is the number of stars per 0.5 mag interval per square arcminute. The solid lines in the top two panels are the observed LFs, while the dashed lines are the LFs corrected for sample incompleteness. The solid lines in the bottom two panels show the difference between the completeness-corrected LFs; in the lowermost panel the background field LF has been scaled up to match the number of stars with $K < 20$ in the galaxy field using the procedure described in §3 in an effort to correct for field-to-field differences in foreground star counts. A statistically significant sample of objects, which we identify as stars in Maffei 1, occurs in the galaxy field when $K > 20.5$.



Galaxy Field
Background Field
K
14
16
18
20
22
H-K
-0.5
0
0.5
1
1.5


Galaxy
Background
Galaxy - Background
Galaxy - Background (Scaled)
log($n_{0.5}$)
0
1
2
3
14
16
18
20
22
K